# SCATTERING OF ULTRASOUND (INCLUDING RAYLEIGH WAVES) BY SURFACE ROUGHNESS AND BY SINGLE SURFACE FLAWS. A REVIEW OF THE WORK DONE AT PARIS 7 UNIVERSITY

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## ABSTRACT

Since some years our team has worked on the characterization of rough surfaces from a study of the angular and frequency dependence of the backscattered intensity of ultrasonic waves. We shall discuss, in view of our experimental results, the different components of the signature of the surface profile which can be evaluated by these means:

-r.m.s. roughness h with a precision of the order of 1 μm in the range 6-100 μm,
-influence of the autocorrelation distance L,
-when present, surface periodicities with a precision which can be better than 1%.

In the case of quasiperiodic surfaces, we shall present a comparison between the spectra theoretically predicted in the low-frequency approximation for various samples, and the ultrasonic spectra actually observed.

Since 1977, we have also used Rayleigh waves to study surface properties and surface cracks in ceramics and metals and we shall give an introduction to the results obtained at the present time. This topic will be developed by B.R. Tittmann in a following paper.

## INTRODUCTION

The scattering of ultrasonic waves by rough surfaces has been studied quite extensively at frequencies below 1 MHz because of its great importance in underwater acoustics. In the field of NDE where the ultrasonic frequencies are one or two orders of magnitude higher, this problem has received much less attention. In certain circumstances of practical interest, the control of surface roughness may be very useful, among them we can quote:

- roughness of the paint on super tankers is one of the main limitations to their velocity,
- roughness of the internal surfaces of vessels submitted to intensive corrosion (chemical and nuclear industries),
- influence of the surface roughness on the propagation and entrance of ultrasound waves and of the roughness of crack faces on the possibility of obtaining the "signature" of these flaws.

We shall describe in the first main section the two experimental approaches used in our laboratory and then present the results obtained on surfaces with random and periodic roughness. The next two sections will be devoted to the problem of natural surfaces where both periodic and random components are present in the profile and to an outline of the work done this year on the characterization of surface flaws by Rayleigh waves.

## EXPERIMENTAL PROCEDURES

In our experiments on the scattering of ultrasound by rough surfaces, we always use water as a coupling medium between the transducer and the surface under test. The transducer acts as transmitter and receiver and the target is placed in the far field of the probe. Two different experimental set-ups are used:

- the first one is derived from a classical narrow-band pulse-echo apparatus which has been fully automated and records the variation of the backscattered ultrasonic energy versus the angle of incidence,
- the second one uses wide-band ultrasonic pulses and signal processing of the received echo including frequency analysis.

### Narrow-Band Apparatus

This equipment has been described elsewhere.[1] The ultrasonic pulses have a duration of 1.5 μs and center frequencies of 2, 5, 15 or 25 MHz; the pulse repetition frequency is 1 KHz. The rotation of the sample is achieved by means of a stepping-motor and each step of the motor corresponds to a variation $\Delta\theta=0.9°$ of the angle of incidence $\theta$, which can be varied from -27° to +27° with respect to normal incidence ($\theta=0$). For each value of $\theta$ in this range, the normalized value $I_\theta=I(\theta)/I(0)$ of the backscattered echo is recorded.

### Wide-Band Experiments. Ultrasonic Spectroscopy -

The ultrasonic pulse emitted has quite a large bandwidth (2 to 9 MHz within 3 dB). The spectrum of the echo received from a perfect reflector is given in Fig. 1. The received signal is amplified and gated in order to select the portion of the signal to be processed (Fig. 2). This time-domain signal can then either be fed to a conventional spectrum analyzer or be sampled, converted to digital, and then processed by the calculator (Fourier spectrum via the F.F.T. algorithm, autocorrelation, ....). The 2000 channels analyzer is used for randomly rough surfaces to calculate the mean value of the spectrum for various parts of the target at the same incidence. It is also used in a rather peculiar way when we extract the periodicity of natural samples by the method of "contracted spectra" (see § IV).

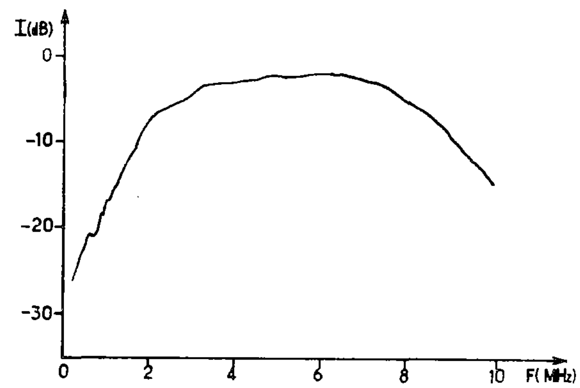


Fig. 1 Ultrasonic spectrum of the signal reflected by a perfect reflector at normal incidence.

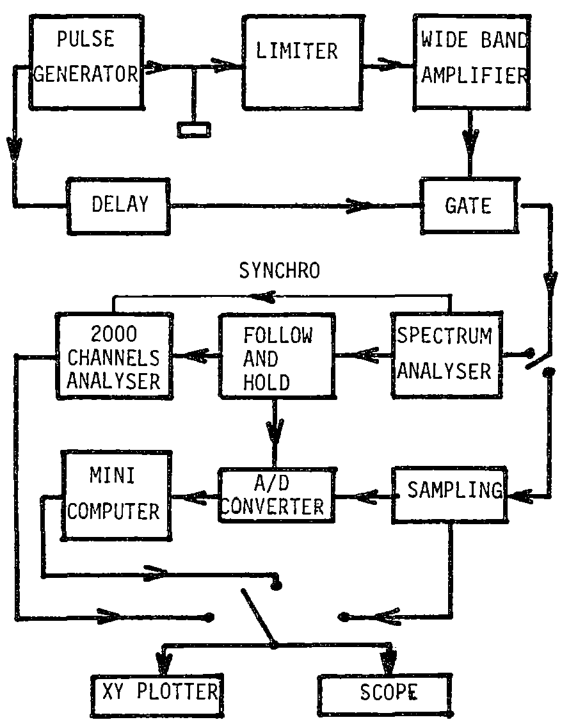


Fig. 2 Block diagram of the electronic equipment (wide-band).

## RANDOMLY ROUGH SURFACES

The main component of the signature of such scatterers is the r.m.s. roughness h of the profile. We had shown previously that the angular variations of the backscattered ultrasonic power are correlated to the value of this parameter and independent of the specific nature of the surface (monocrystal, metal, paint, tissue). We have recorded in the memory of the calculator the results obtained for surfaces with a known value of h. Examples are given in Figs. 3 and 4 for roughnesses ranging from 5 to 93 μm studied at 5 MHz.

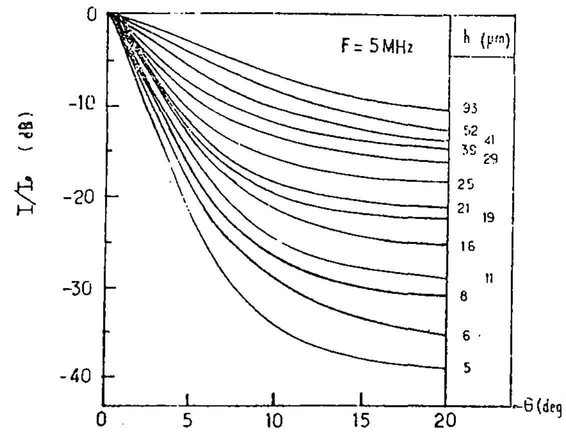


Fig. 3 Plot of the variations of the normalized backscattered ultrasonic intensity $I_\theta$ versus the angle of incidence for various value of the r.m.s. roughness h.

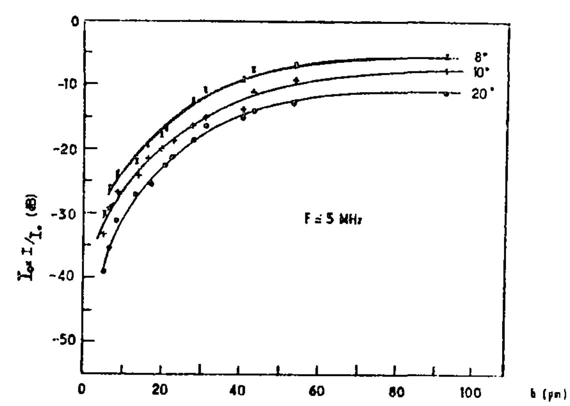


Fig. 4 Plot of the variations of the normalized intensity $I_\theta$ versus the r.m.s. value of the roughness h.

When we want to obtain an ultrasonic estimate of the roughness of a given surface, we put the sample in the apparatus and the calculator controls the whole experiment, records the backscattering diagram for angles of incidence varying from -27° to +27°, and calculates the mean value $\overline{I}_\theta$ for n sets of experiments corresponding to the same angle of incidence θ but on different parts of the sample, or corresponding to rotation of the surface in its own plane. Then the calculator uses the least square method to obtain an analytical form of the function $\overline{I}_\theta = f(\theta)$, makes a comparison with the reference values (Figs. 3 and 4) and displays the ultrasonic estimate of h and its absolute error Δh.

We see in Fig. 4 that for roughness greater than 40 μm at 5 MHz, the curve $I_\theta(h)$ tends to saturate, leading to a bad estimate of h along this procedure. For samples exhibiting quite a large roughness, we use a smaller ultrasonic frequency (2 MHz). For very small values of the roughness (<5 μm) at 5 MHz, the scattering is almost only specular and better measurements are achieved at higher frequencies (15, 25 MHz).

The procedure leads to an estimate of the value of the roughness h with a precision of 1 μm in the range (5μm<h<40μm) and 2 μm for higher values of h. Ultrasonic spectroscopy has also been applied to the characterization of rough surfaces. We have plotted in Fig. 5 the normalized spectrum $[I(\theta)/I(\theta=0)]$ of the signal backscattered by two different randomly rough surfaces insonified at an angle of incidence of 4°. The frequency content of the signal is the same for the three experiments at frequencies smaller than 3 MHz, but the difference between the spectra of higher frequencies is characteristic of the roughness. Some oscillations are observed in the spectrum for sample c because its profile has a noticeable periodic component.

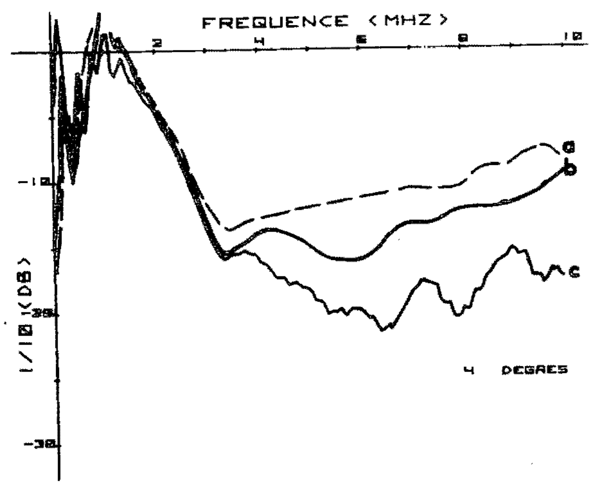


Fig. 5 Normalized spectrum of the signals back-scattered from randomly rough surfaces: a) h = 18μm, b) h = 13μm, c) h = 8μm

Experiments are beginning on the scattering by back surfaces of random roughness where the ultrasonic beam enters a metallic slab by a smooth surface.

## PERIODICALLY ROUGH SURFACES

For periodically rough surfaces, ultrasonic spectroscopy has proved to be a very powerful means of profile characterization.

Like in optics, the spectrum of the signal scattered by a diffraction grating exhibits diffraction lines corresponding to the different orders n of diffraction. Their frequencies $f_m$ are given by Bragg's formula

$$2\Lambda \sin\theta = m\lambda = m(v_S/f_m) , \qquad (1)$$

where $\Lambda$= grating spacing constant, $\lambda$ = wave length, $\theta$ = angle of incidence (autocollimation), and $v_S$ = velocity of sound.

Figure 6 represents the spectrum of the signal diffracted by a grating (Λ=400μm) for an angle of autocollimation of 70°. This spectrum has not been corrected by the spectrum of the incident pulse. Four sharp diffraction lines corresponding to the fundamental and three first harmonics (m=1,2,3,4) are observed.

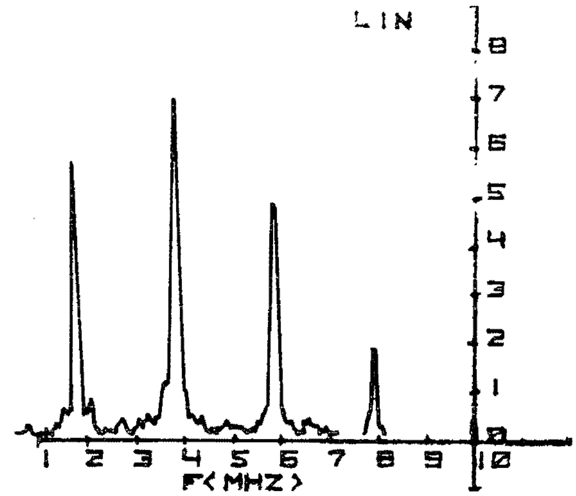


Fig. 6 Spectrum of the signal diffracted by a grating (Λ=400μm) at an angle of autocollimation θ=70°.

The most precise determination of the periodicity Λ of the grating is obtained by plotting (Fig. 7) the frequencies $f_m(\theta)$ of the diffraction lines obtained at various angles of incidence versus $1/\sin\theta$. Bragg's relationship can be written

$$f_m = m(v_S/2\Lambda)(\sin\theta)^{-1} \qquad (2)$$

and we obtain one straight line for each order of diffraction. The value of Λ is then deduced from the slopes of these lines. The precision attained by this method on the estimate of Λ is better than 1%.

This method has also been applied to samples presenting a periodicity along two mutually perpendicular directions and we have shown[1,2] by a comparison between the results obtained with a true square lattice engraved in lead and that obtained for a grid with a square mesh that this technique is sensitive to the true periodicity in the crystallographic sense for which the grid is 2a along the wires if a is the length of the side of each square.

We have also explained[2] how the periodicity can be deduced from the angular scattering diagram obtained in narrow-band experiments with a precision of the same order.

We had observed previously that for gratings exhibiting defects in periodicity, "Rowland ghosts" are present in the ultrasonic spectra. These secondary diffraction lines correspond to sub-gratings with periodicities 2Λ, 3Λ, 4Λ, 5Λ. As many as 17 such ghosts have been observed for a poor periodic grating where the grooves were equally spaced, but had different depths. All these "Rowland ghosts" can be plotted on the graph $f_m(1/\sin\theta)$ and are disposed along straight lines corresponding to the order of diffractions m=n/p where n and p are integers (diffraction by the sub-grating pΛ). We could roughly correlate these properties of the ultrasonic spectra with the periodicity defects of the autocorrelation function of the profile.

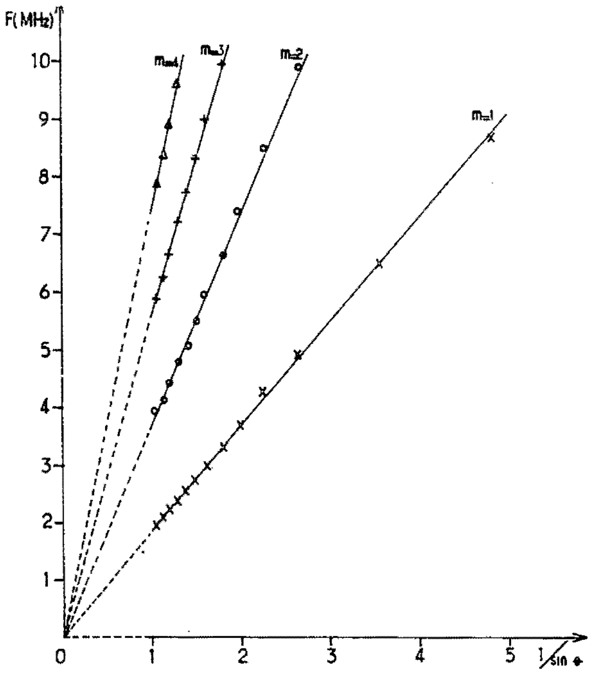


Fig. 7 Plot of the frequencies $f_m$ of the diffraction lines of order m versus (1/sinθ) for a diffraction grating with a spacing constant Λ = 400μm.

In 1976-77[3] we have successfully applied the Kirchkoff method in the low frequency approximation to deduce from the known profile ξ(x) of a given grating the ultrasonic power spectrum diffracted at a given frequency f and angle of autocollimation θ.

For a grating with a spectral periodicity Λ (along an axis x of the surface), the amplitude of the diffracted wave A(f,θ) for an incident plane wave is given by

$$A(f,\theta)=G_1(\theta)\int_{-L}^{+L} \exp\{2ik[x\sin\theta-\xi(x)\cos\theta]\}dx \qquad (3)$$

where 2L is the length of the grating and k the magnitude of the wave vector of the ultrasonic waves. Many theoretical approaches leading to this same formula[4,5,6] differ only by the angular dependence factor $G_1(\theta)$.

In the low frequency approximation

$$2k\ \xi(x)\cos\theta \ll 1\ , \qquad (4)$$

$$A(f,\theta) = fG_2(\theta)\int_{-L}^{+L} \exp\left[\frac{4i\pi fx\sin\theta}{V_S}\right]\xi(x)\,dx \qquad (5)$$

and the amplitude of the $m^{th}$ diffraction line for a perfect grating is proportional to the $m^{th}$ coefficient of the development of the profile ξ(x) in Fourier series.

In order to test the validity of this very simple theoretical approach, we have built 8 diffraction gratings exhibitng different profiles (peak-to-valley heights: 4μm<R<23μm), but having the same periodicity (Λ=400μm). The profile of each grating has been measured with a sampling distance of 40 m and the values obtained are used in the subsequent theoretical calculations of the Fast Fourier Transform of the profile.

Figure 8 is a theory versus experiment comparison for the values of the intensities of the two first diffraction lines (m=1,2) and two different angles of autocollimation (θ=62°,70°). The values indicated in dB are normalized versus the value obtained for the roughest of our 8 samples. The correlation $r^2$ is equal to 0.95 and the slope of the regression line is very close to 1 (1.03).

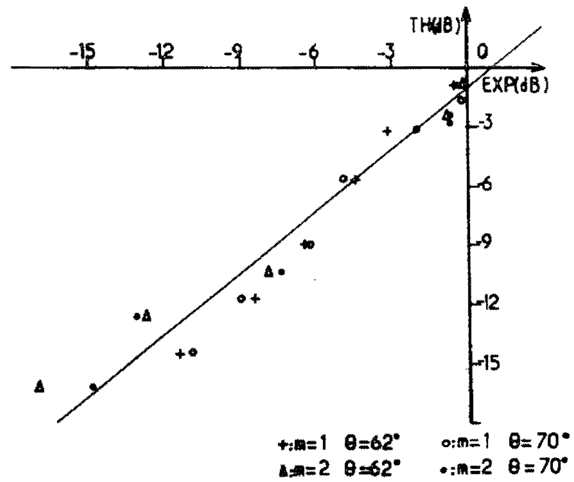


Fig. 8 Experimental values of the ratio $I_{mi}(\theta)/I_{nj}(\theta)$ versus the theoretical ones $I_{mi}(\theta)$ = Intensity of the line of order m for sample i.

In Fig. 9, we present a comparison between the ultrasonic spectra and the spectra computed from the F.F.T. of the profile and corrected for the spectrum of the incident ultrasonic pulse. The comparison is only valid for frequencies smaller than 5 MHz, which corresponds to the limit of validity of the low-frequency approximation that we use.

Figure 9-1 corresponds to the roughest sample (R=23μm) and Fig. 9-2 to a smoother one (R=8.4μm). A rather good agreement exists between the experimental results and the theoretical expectations, especially for the diffraction lines. The background between the peaks is not very well predicted and this "noise" is generally greater in the theoretical result than in the experimental one. Two explanations can be given for these discrepancies: 1) the non-uniformity of the insonification of the grating and the shape of our electronic gate which can give rise to a smoothing of the spectrum between the lines (like the Hanning window in F.F.T. computations); 2) the lack of a statistical treatment of different profiles

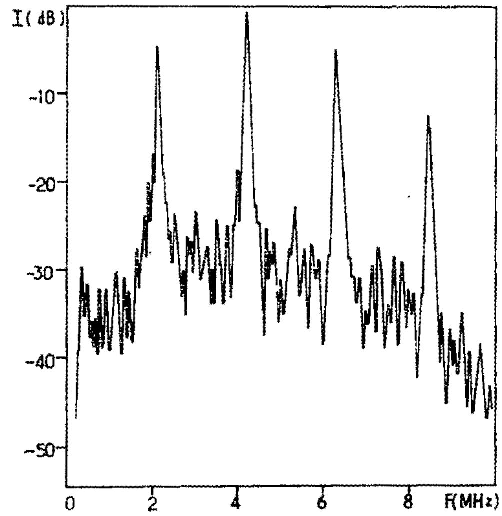


Fig. 9-1(a)

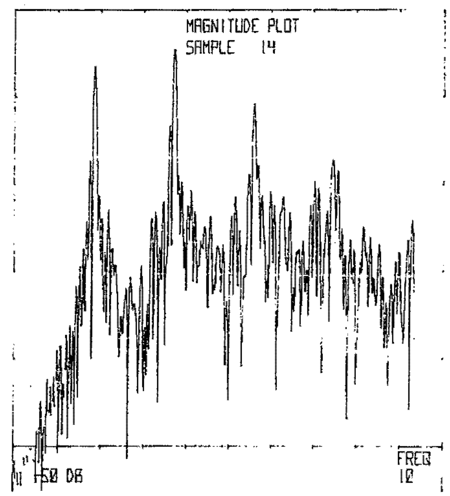


Fig. 9-1(b)

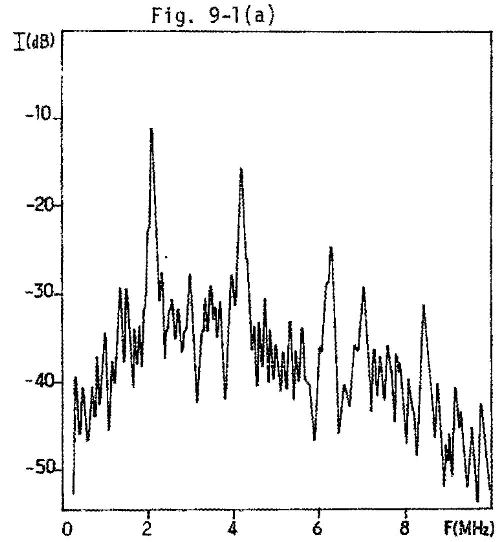


Fig. 9-2(a)

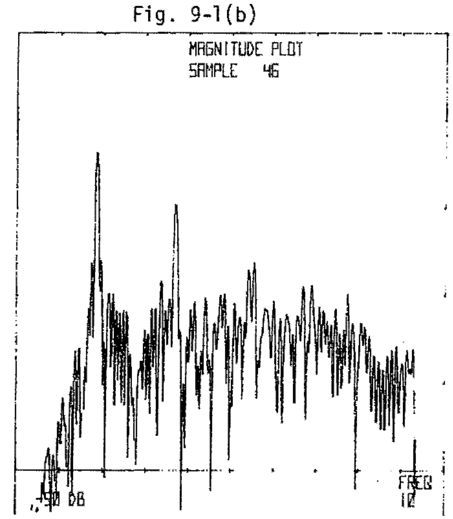


Fig. 9-2(b)

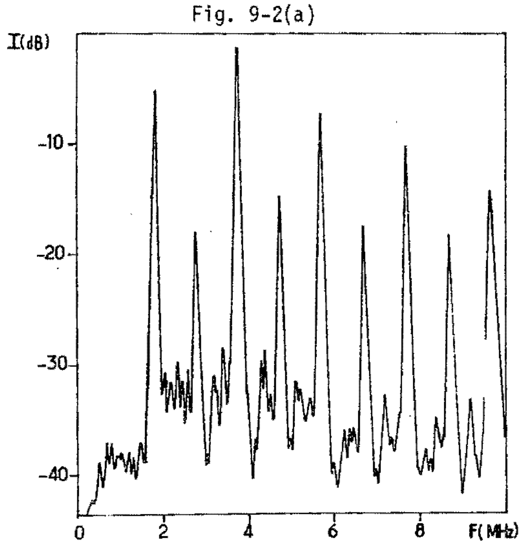


Fig. 9-3(a)

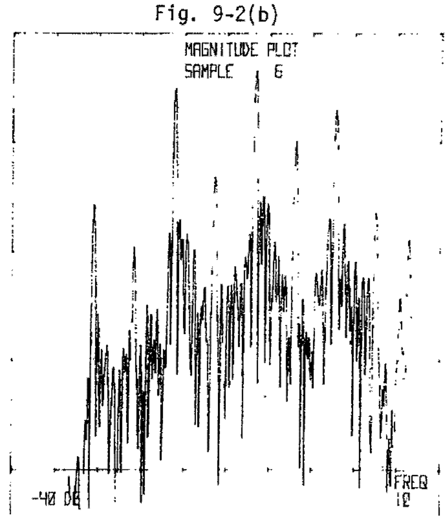


Fig. 9-3(b)

Fig. 9 Comparison between a) ultrasonic spectrum; b) spectrum computed from the F.F.T. of the profile (corrected)

## SCATTERING OF RAYLEIGH WAVES BY SURFACE FLAWS

During the stay of B.R. Tittmann in our laboratory, we began a set of experiments in this field, and I want only to introduce the paper that he will give in this same session. We have studied penny-shape surface flaws in ceramics and metals. The radius of the flaws where less or equal to 100μm in ceramics and of the order of one millimeter in metals and three different techniques have been used for the generation of surface waves: SAW delay line in contact with the surface for high frequency experiments (100 MHz), wedge transducers for low frequency narrow-band experiments (2 to 10 MHz), water bath coupling for wide band experiments at low frequencies (2 to 9 MHz). The first parameter that we have been able to measure ultrasonically is the radius of the cracks with a 10% accuracy.[7]

## CONCLUSION

We have shown that with good accuracy, ultrasonic backscattering experiments can lead to an estimate of the first statistical parameter characteristic of randomly rough surfaces: the r.m.s. roughness h. At the present time, we are not able to deduce from our experiments the values of the autocorrelation distance L of the profile; the influence of this parameter on the backscattering is much less than that of the roughness. For periodically rough surfaces, it is quite easy to measure ultrasonically the periodicity with a precision better than 1%, both using narrow-band or wide-band pulses (ultrasonic spectroscopy). We have also been able to predict theoretically quite correctly the spectra of the echoes diffracted from gratings in the low frequency range. Nevertheless, the inverse problem remains unsolved and we continue its study. For "natural" surface, we have shown that the method of summation of "contracted spectra" is very powerful to detect hidden periodicities.

Besides rough surfaces, we also are studying the scattering of ultrasound by surface cracks and by cylindrical targets, but I also want to emphasize the good results that we have obtained for the characterization of living tissues.[8] For this purpose we use an extension of the techniques developed in this paper. A review of our results in that field will be presented at the 1978 Ultrasonics Symposium.

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sampled along parallel lines perpendicular to the direction of periodicity (the theoretical calculation uses only one profile and small local inhomogeneities are present in the samples). Fig. 9-3 corresponds to a grating with inhomogeneities related to a sub-grating with a periodicity $2\Lambda$ and the "Rowland ghosts" observed are predicted by the theoretical calculation.

## NATURAL ROUGH SURFACES

The profile of a natural surface has both a periodic and a random component. The signature of such a scatterer must contain information about these two components. We have proposed a method ("contracted spectra") leading to an ultrasonic estimate of the periodicities of the profile, even when its main part is random. This method is based upon Bragg's formula which can be written

$$f_m \sin\theta = m v_S / 2\Lambda \qquad (6)$$

One can deduce that if, instead of recording the spectrum I(f), we record the "contracted spectrum" $I(f \sin\theta)$, in the second one the diffraction line of a given order m occurs for all values of the angle $\theta$ at the same abscissa $f_m \sin\theta$. The procedure uses the 2000 channels analyzer (Fig. 2). For each angle of incidence $\theta_i$, the sweep time of this apparatus is adjusted in order that only the ($2000 \sin\theta_i$) first channels of the analyzer are filled during the time T of readout of the whole spectrum (0,10 MHz) from the spectrum analyzer. For each rough sample a set of n experiments ($N \approx 20$) is performed using different values $\theta_i$ ranging from 14° to 70°, and the analyzer carries out the summation of these "contracted spectra" $I(f \sin\theta_i)$ and finally displays the corresponding curve

$$\sum_{i=1}^{n} I(f \sin\theta_i)$$

This is illustrated in Fig. 10 where you can compare the very messy spectrum observed with a rough surface where the main component of the profile is random and the rather nice result of the summation of 22 "contracted spectra" exhibiting three diffraction lines. From the values of $f_m \sin\theta$ we deduce for this sample a spatial periodicity $\Lambda_{exp} = (395 \pm 7)\mu m$. Actually, this sample has been made by first engraving in lead a grating with a spacing constant $\Lambda = (400 \pm 2)\mu m$ and then roughening the surface until the grooves become unnoticeable, even on a microphotograph (Fig. 10a).

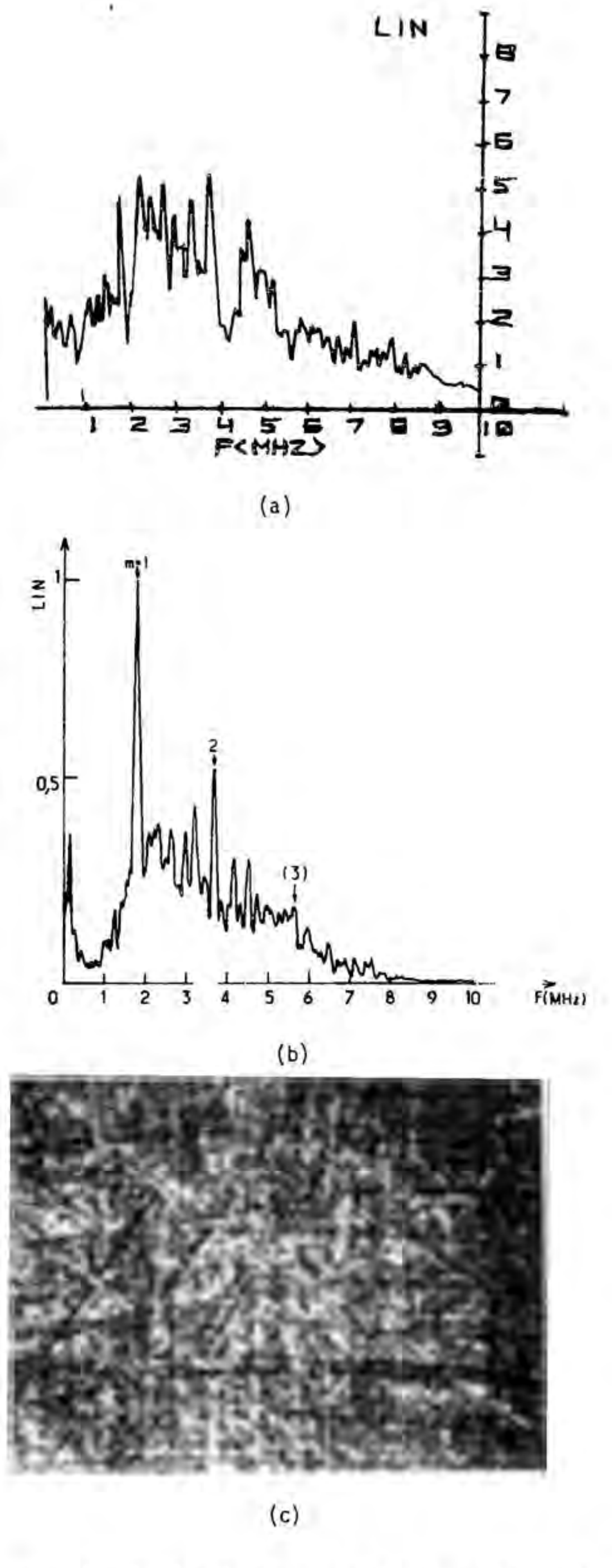


Fig. 10 - Sample 34. Comparison between the spectrum displayed on the frequency analyzer (a), and the content of the 2000 channels when 22 experiments have been performed using the procedure described in the text, (b); a microphotograph of the surface of the sample is given in (c).

DISCUSSION

G. Hermann (Stanford University): I was wondering if there are any practical situations where periodic surface roughness exists?

G. Quentin (University of Paris VII): Yes. In a practical situation materials which have been machined always have a periodic roughness if they are not polished. Usually in industry you don't polish the sample. It is only physicists which polish samples. Another point that I did not mention concerns roughness and random roughness. Random roughness seems to appear even on a polished surface.

G. Hermann: Under the periodic structure on the periodic surface properties, you have made measurements on periodic gratings which you have manufactured yourself in the lab?

G. Quentin: Yes, but some work has been on metal surfaces machined in the usual fashion.